Subsidence Due to Abandoned Mining in the South Wales Coalfield, U.K.: Causes, Mechanisms and Environmental Risk Assessment

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ABSTRACT Recent research on South Wales mining subsidence has assembled a database of over 400 subsidence incidents attributable to abandoned mining. Over 75% were collapses into workings at outcrop; or mine entrances. The remainder were almost always crownholes, whose upper limit of migration through rock was generally 8 to 12 times the void height.

Two thirds of the incidents occurred in open land and their environmental and economic impact was nominal. About 16% caused damage to roads and structures. Only one example of injury was traced, although about 20% occurred in areas where people pass frequently.

Taken as a whole, the database has shown a very low probability of a subsidence causing damage to property or injury to people. Expenditure on preventive measures vastly exceeds remedial expenditure, indicating that perception of the risk is out of proportion with the consequences. Engineering strategies for protecting existing and proposed developments should recognise that different levels of risk apply to different mining situations, so that resources are used to best advantage.

INTRODUCTION

South Wales has a tradition of mining on an industrial scale extending back more than 200 years. Mining has now virtually ceased, although periodically surface subsidence occurs as the abandoned workings continue to deteriorate.

Recent Department of Environment/Welsh Office research contracts (see Statham et al 1987) have assembled a database of over 400 subsidence incidents, for the South Wales Coalfield allowing a review of the risk to be carried out on a coalfield wide basis. Such opportunities are rare, although similar assessments have been made by Bruhn et al (1980) for the Pittsburgh Coal Bed and Cole et al (1984) for Limestone Mining in the West Midlands of the U.K.

In this paper, causes, mechanisms and environmental effects of subsidence due to abandoned mineworkings are discussed. The level of risk and economic consequences are then assessed, in the light of current expenditure on remedial and preventive measures. In
the past, subsidence processes and effects have been severe at, and shortly after, the time when the mining occurred. The purposes of this study, however, are to identify the current, residual subsidence effects since it is these, and the prospects for the future, which are relevant to present day development and planning.

THE SOUTH WALES COALFIELD

Geology

The South Wales Coalfield is an elongate synclinal structure, some 100km by 40km; see Figure 1. It is divided by a major fault system, the Neath Disturbance, which crosses from NE to SW with a downthrow of over 650m to the west. To the east, the northern limb of the syncline dips at about 1 in 10, whilst the southern limb is steeper, at up to 1 in 2. West of the Disturbance the structure is complex, with many reverse faults and thrusts.

FIG. 1 The South Wales Coalfield.
A characteristic of the coalfield is the large number of coal and stratigraphic iron ore horizons which have been worked in a relatively small thickness of strata. This is particularly so in the Lower and Middle Coal Measures. The seams are normally thin, 0.5m to 2.0m being typical, although collectively they add up to a considerable thickness of extraction in many places.

Mineral History

Coal and iron ore have been mined for centuries in some parts of the coalfield. However, pre-industrial mining has largely been obliterated by later operations.

Large scale mining started in the south-west of the coalfield in the 16th and 17th centuries, serving a sea-based export trade centred on Llanelli; see Figure 1.

Widespread industrial mining began in the north-east from about 1760 onwards, see Figure 1, associated with iron manufacture. Rapid expansion occurred as communications developed and the area was almost completely worked out by the end of the 19th century. Iron smelting spread slowly to other areas around the margins of the coalfield, but not to the same extent. In particular, progress was inhibited in the north-west, since the anthracite grade coals found in this area were unsuitable for smelting in early iron technology.

Mostly, the centre of the coalfield remained undeveloped until the mid 19th century. Here, the seams were deep and it took the enormous demand for steam coal in the mid 19th century to stimulate the necessary improvements in mining technology to exploit these deep reserves. Development peaked around the First World War at more than 50 million tons per year.

There has been a steady decline throughout the 20th century, accelerated recently by major rationalisation of the British Coal Industry. Now, only five collieries remain open and over most of the coalfield, mining is rapidly passing into history.

CAUSES AND MECHANISMS OF SUBSIDENCE

Data

Records of over 400 subsidence incidents have now been collected, forming a comprehensive database of recent subsidence processes associated with abandoned mining. Most records have been collected from the British Coal Corporation and local government departments, the majority dating from 1960 onwards.

Causes

Records usually consist of scanty details of location, consequences and sometimes remedial measures. Establishing the cause of subsidence involved a review of the geology and available mining records for each incident. Table 1 summarises the findings. The main points arising are:

(a) Some 75% of incidents were caused by collapses at mine
TABLE 1 Causes of subsidence incidences.

<table>
<thead>
<tr>
<th>CAUSE</th>
<th>NUMBER OF INCIDENTS</th>
<th>PERCENTAGE OF TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recorded Adit Entrances</td>
<td>120</td>
<td>30.3</td>
</tr>
<tr>
<td>Unrecorded Adit Entrances</td>
<td>25</td>
<td>6.4</td>
</tr>
<tr>
<td>Recorded Shafts</td>
<td>64</td>
<td>16.1</td>
</tr>
<tr>
<td>Unrecorded Shafts</td>
<td>7</td>
<td>1.8</td>
</tr>
<tr>
<td>Recorded Outcrop Workings</td>
<td>12</td>
<td>3.0</td>
</tr>
<tr>
<td>Unrecorded Outcrop Workings</td>
<td>78</td>
<td>19.6</td>
</tr>
<tr>
<td>Recorded Adits below Rockhead</td>
<td>21</td>
<td>5.3</td>
</tr>
<tr>
<td>Unrecorded Adits below Rockhead</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Recorded Workings below Rockhead</td>
<td>37</td>
<td>9.7</td>
</tr>
<tr>
<td>Unrecorded Workings below Rockhead</td>
<td>31</td>
<td>7.9</td>
</tr>
<tr>
<td>Cause Unknown</td>
<td>8</td>
<td>Excluded</td>
</tr>
</tbody>
</table>

77.2% of incidents relate to collapses through superficial deposits or in fill
22.8% of incidents relate to collapses of workings below rockhead

exclusions or at the outcrop of the seam; i.e. there was no rock cover to the part of the mine which collapsed to cause the subsidence.
(b) Mine entrances pose by far the biggest risk, over 50% of the total, most of which are recorded.
(c) More than 80% of the mine entrance incidents occurred at recorded features.

These three points are encouraging. Clearly the vast majority of subsidence incidents occur within well defined, easily locatable zones which form a very small part of the total area of the coalfield.

Failures of Mine Entrances

Mechanisms of subsidence due to collapse of adits and shafts have been discussed elsewhere (e.g. Dean 1962, Edmonds 1989, Statham and Gordon 1990; NCB 1982). The main causes are:
(a) Structural failure due to decay, e.g. of adit supports within the superficial deposits (masonry, timbers or steel rings) or shaft liner.
(b) Failure of backfill to a shaft or adit by consolidation, or rapid slumping due to washing out.
(c) Failure of inadequate or decayed cappings placed over open entrances.
Subsidence Due to Collapse of Workings below Rockhead

As Table 1 shows, subsidence due to adits and workings below rockhead only account for 90 incidents, about 25% of the whole set. However, it is particularly important to understand their mechanisms because:

(a) Their locations are less predictable than mine entrances and outcrop workings.
(b) They define the 'upper bound' of the subsidence process and hence the limits of areas at risk.

The vast majority of subsidence incidents where a rock cover was formerly present over the workings are 'crownholes' in form. That is, they have developed by migration of the void upwards through the roof strata by progressive collapse, forming a chimney; see Figure 2.

![FIG. 2 Formation of chimneys, stable arches and crown holes.](image)

The upper limit to this process has been the subject of many papers on abandoned mining subsidence for over 30 years. Most efforts have been directed at deriving empirical relationships between maximum height of void migration and the geometry of the collapse chimney, taking bulking of the collapse debris into account (for example, Tinscelin, 1958; Piggott and Eynon, 1978; Whittaker and Reddish, 1989). Most calculations arrive at an upper bound for chimney height ($H$) of around $8T$, where $T$ is the thickness of strata extracted, or original height of void.

Recently, Garrard and Taylor (1988) presented the results of a study of abandoned workings found at British opencast sites and concluded, by a combination of theoretical and empirical analysis, that the upper limit of migration was controlled by the formation of stable arches, not choking by bulked collapse debris. Height of migration was generally limited to less than $3W$, where $W$ is the width of the void.

There is a third possibility, where no stable arch can form, e.g. in shattered or faulted zones with groundwater ingress and where no bulking occurs. The latter may be due to washing away of collapse debris by water moving through the mine, or by slipping
to greater depth down steeply inclined workings. In these cases, the height of migration is indeterminate and could greatly exceed the limits given above.

In South Wales, the process of collapse of workings generally results in the formation of crownholes. Only two examples of general subsidence, i.e. subsidence of a wider area without formation of a collapse feature, have been found in the studies. These probably related to pillar failures.

The height of migration of crownholes has been analysed for the 90 incidents where a rock cover was formerly present above the workings. In some cases, the actual values of $H$ and $T$ were recorded at the time of collapse but in most cases assumptions had to be made. $H$ was derived from topographic maps, mine plans and geological maps, whilst a standard roadway height of 2m was assumed for $T$. The results are, therefore, not necessarily absolute but if they are applied consistently they can be used as a predictive tool within the area from which they were derived, i.e South Wales. For other areas, a similar coalfield wide study of subsidence would be necessary, since the limit to migration would not necessarily be the same.

Figure 3 is a histogram of $H/T$ vs percentage of incidents. It shows that the upper bound for South Wales is about 18, although in 90% of cases $H/T$ was less than 6. A comparison is made with data in Bruhn et al (1981) which shows that different coalfields can have different forms of histogram and upper limit to

\[ \text{FIG. 3 } H/T \text{ vs percentage of incidents.} \]
subsidence. The differences reflect variations in mining methods and geological conditions.

The form and upper limit to the histogram give some clues about controlling mechanisms; stable arching or bulking. H/T on Figure 3 could be read as W/T, since roadways are also typically about 2m wide. Reading it this way, around 80% fall below W/T <3, suggesting that stable arching could well be a controlling mechanism in most cases. However, for incidents where 3<W/T<18, stable arches could not have formed and thus bulking is the limiting mechanism. Typically, stalls (rooms) in South Wales mines were approximately 5m width; hence even if the higher values of W/T related to stalls, the maximum ratio would still be 18 x (2/5) = 7.2, well above Garrard and Taylor's limit for stable arching. It follows that, whilst stable arching may be a common controlling collapse mechanism, it does not control the upper bound and cannot be used to predict areas at risk of crownholing.

It is worth noting that more than a dozen incidents on well recorded mine adits have been collected where the H, T and W were accurately known and where calculated values of H/T (or W/T) were in the range 6 to 10.

ENVIRONMENTAL IMPACT AND PROBABILITY OF SUBSIDENCE

Nearly two-thirds of incidents (64%) occurred in open ground, well away from structures. A further 14% occurred close to buildings but caused no actual damage.

Damage occurred in 16% of the incidents; 9% to roads and 7% to buildings. Mostly, the damage to buildings has been minor. In a few cases, substantial works have ensued but these have largely been towards preventing the spread of damage or future occurrence of similar subsidence. There have been occasional examples where demolition has been considered necessary.

Incidents causing damage have averaged less than 3 per year over the last 30 years, a low rate of occurrence when the size of the coalfield is considered.

About 6% of incidents occurred on construction sites, and could be regarded as a threat to life. Actually, only one injury has been recorded and there have been no fatalities.

An estimate of the assumed probability of subsidence occurring at any site can be made as follows:

\[ P = \frac{N_i}{A_i} / T A_c \]

Where P = probability, N_i = no of incidents recorded, T = time period, A_i = area affected by an incident (taken as 5m x 5m), A_c = area of coalfield. This results in an average probability for any point in the coalfield of about 1x10^{-7}/annum. For mine entrances and areas within 100m of seam outcrops, values of 1x10^{-4}/annum and 5x10^{-5}/annum respectively apply. The level of risk for the remainder of the coalfield is in the region of 1x10^{-8}/annum.

Cole (1987) has considered the notions of 'degree of risk', 'severity of consequences' and 'public tolerance' to derive a matrix of risk acceptance or tolerance by society. The levels of risk given above for subsidence in South Wales are compared in Table 2. The Table is a first approximation at a strategy for tackling the mining subsidence risk in South Wales. It highlights the importance of seam outcrops and mine entrances and shows that,
TABLE 2 Annual risk of subsidence due to abandoned mining in South Wales.

<table>
<thead>
<tr>
<th>LOCATION IN COALFIELD</th>
<th>ANNUAL RISK LEVEL</th>
<th>RISK CLASSIFICATION* TO LIFE</th>
<th>RISK CLASSIFICATION* TO PROPERTY</th>
<th>PUBLIC EXPECTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Coalfield</td>
<td>$1 \times 10^{-7}$</td>
<td>Very unlikely</td>
<td>Negligible</td>
<td>About what would be expected in a mining area for structures</td>
</tr>
<tr>
<td>At Mine Entrance</td>
<td>$1 \times 10^{-4}$</td>
<td>Some Risk</td>
<td>Unlikely</td>
<td>Not acceptable in public buildings, work places or houses</td>
</tr>
<tr>
<td>Near Seam Outcrops</td>
<td>$5 \times 10^{-6}$</td>
<td>Slight Chance</td>
<td>Unlikely</td>
<td>About what would be expected in open spaces in a mining area</td>
</tr>
<tr>
<td>Elsewhere (away from entrances and outcrops)</td>
<td>$1 \times 10^{-8}$</td>
<td>Practically</td>
<td>Impossible</td>
<td>Better than would be expected in a mining area for structures</td>
</tr>
</tbody>
</table>

* see Cole (1987)

in any event, there are areas where preventive measures would be expected in construction projects. Elsewhere, there is a much lower risk, well within that which would be normally tolerated by the public. These generalisations are no substitute for detailed site assessment and a judgement of the level of risk at each site still has to be made. Nevertheless, they do serve to show that the concept of risk can be introduced into engineering decisions.

REMEDIAL VERSUS PREVENTIVE EXPENDITURE

It is interesting to compare the costs of remedial works to properties affected by abandoned mining subsidence with the costs of preventive measures, used to protect existing and new buildings 'at risk'. A pilot survey of a large property estate in the coalfield revealed an average expenditure over 6 years on remedial works was about £3000/annum; the range per incident was from nominal expenditure to over £35,000. These figures represent the cost of rectifying the actual damage and do not allow for consequential costs, or preventive measures deemed necessary to stabilise the remainder of the site. A study of over 30 sites where preventive measures were carried out revealed that the average annual expenditure was about £200,000, an average contract costing over £40,000.

It is clear that the preventive expenditure is out of proportion with the risk; the amount spent on preventive measures exceeding that spent on remedial work by a factor of 60. This, in conjunction with the assessment of risk to property and people
Subsidence due to abandoned mining in South Wales, U.K.

discussed above, shows that the response to the abandoned mining hazard tends to be irrational, leading to an unbalanced use of funds.

CONCLUSIONS

The following conclusions can be made:
(a) Subsidence incidents due to abandoned coal mining in South Wales are confined mainly to occasional crownholes and collapses at mine entrances; very few examples of general subsidence are now occurring.
(b) The majority of migrating voids are limited by the formation of stable arches. However, the upper limit of crownholing appears to be controlled by bulking of collapse debris, and therefore bulking should be taken as the 'design process' for engineering decisions.
(c) The risks of future subsidence incidents are by now low; at an average of some $1 \times 10^{-7}$/annum for the coalfield as a whole. Locally, the risks of future subsidence incidents, are much higher at mine entrances and near to seam outcrops.
(d) Overall the risk of subsidence incidents causing damage to property or injury to people, are overestimated, resulting in unwarranted expenditure on preventive measures in relation to existing and new structures. Only around mine shafts and near to seam outcrops is the risk high enough to warrant extensive preventive expenditure in the ground. Elsewhere, measures incorporated into the structures, e.g. raft foundations, are a more appropriate solution.

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REFERENCES


